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Case Study

Performance of seismic detectors: a case study of the sensitivity of SM-4 geophones used in Nigeria

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Abstract

A vibration test was conducted on a typical SM-4 Geophone used for seismic data acquisition in Nigeria to determine its sensitivity which is important for high-resolution seismic exploration. The Geophone planted in a sand box, picked up mechanical vibrations of different frequencies generated using a signal generator. Weak signals were enhanced and the range of signals compressed by an amplifier connected to the Geophone. These signals were displayed on a high resolution Cathode Ray Oscilloscope and the velocity (m/s), voltage (V) and resistance (Ω) were measured using Digital Multimeter. The sensitivity (V/m/s) of the Geophone was computed for different frequency bandwidths: 0.5-10Hz, 5-100Hz, 50-1000Hz, 500-10000Hz and 5000-100000Hz using the Transduction equation. Results from Frequency-Sensitivity response curves show that for 0.5-10.0Hz, sensitivity exponentially increased to maximum of 37.40V/m/s with a natural frequency, f_0 of 2Hz and decreased afterwards. For 5-100Hz, the sensitivity decreased exponentially with increasing frequency from 7.41 to 1.31V/m/s. At a further bandwidth of 50–1000Hz, f_0 disappears. The sensitivity decreases exponentially with increasing frequency from 0.75 to 0.71V/m/s. The sensitivity further decreases exponentially with an increase in bandwidth from 500-10000Hz. For 5000-100000Hz, sensitivity decreases exponentially from 0.25 to 0.00V/m/s. This is as a result of distortion in the Geophone element. The characteristic coil resistance decreased to 100Ω and this caused the Geophone sensitivity to approach zero, hence deteriorating performance. This study will help acquisition seismologists in mitigating the consequences of premature Geophone failure, particularly as they affect data quality, performance and the overall running cost of the seismic acquisition scheme.

Keywords: Sensitivity, Frequency, Digital Multimeter, SM-4 Geophone, Cathode Ray Oscilloscope. Transduction.

Introduction

The acquisition of high quality seismic data, to a large extent, depends on the performance of seismic detectors during field operations by seismic exploration companies. Seismic detectors are the most vulnerable part of the seismic acquisition chain. They are in need of constant quality control and maintenance through various tests to improve their performance[1]. This has increased interest in research into the parameters on which Geophone's operating performance hinges.

The operating performance of Geophones can be quantified by conducting various tests to determine the qualitative status of the Geophone's five key parameters: coil resistance, natural frequency, damping, distortion, and sensitivity with an indication whether test results fall inside or outside manufacturers' specified limit.

Hence, instrument and vibration tests of strings of Geophones in use, preferred seismic crew quality control procedures, are standard quality control measures to be conducted as a prerequisite to the successful acquisition of high quality and reliable seismic data.

Several studies which measured the response of Geophones in the laboratory had been conducted[2,3]. However, there appear to be only a few which deal with Geophone performance in the field. Besides, aspects of Geophone coupling in laboratory and field experiments for vertical as well as horizontal elements have been studied[3,4]. This paper presents the results of a laboratory investigation into the sensitivity of SM-4 Geophone widely used for seismic exploration in Niger Delta. The aim is to mitigate the consequences of premature Geophone failure which negatively affects acquisition efficiency and expense of seismic crew. In specific terms, the dependence of voltage, velocity, and sensitivity of Geophone element on frequency was analyzed. Several operating bandwidths were considered.

Features of a typical SM-4 geophone

The SM-4 Geophone is a third generation digital grade Geophone with the element designed for low weight, long field-life, high output and ultra-reliable performance. Its precision-engineered components ensure consistency in manufacture and operation throughout and beyond the limited replacement guarantee period of three years. SM-4 Geophones are employed in 2-D and 3-D seismic exploration with bandwidths from 8 Hz up to 190 Hz[5].

It has excellent electrical characteristics and manufactured to close tolerance with rotating coil construction minimizing the forces on the spring. Hence, it has a very high sensitivity, low distortion and low damping of ±5% tolerance at a frequency of 10 Hz[6].

The SM-4 Geophone has a reinforced polyester case consisting of a marsh case, a marsh shank and a gland screw to ensure that the Geophone stands up to rough handling and remains within specification. It has a spike made of steel or brass to ensure optimum electrical contact. The length of the brass spike is 2.5 inches (60 mm) among other dimensions. Tight frequency and damping tolerances of ±5% each provide for the smallest phase shift. Four stainless steel screws hold down the marsh shank on this completely water proof case. An ultraviolet (UV) stabilized rubber sleeve or gland provides stress relief as the cable enters the geophone case. An O-ring (mechanical gasket or loop) and spacer O-ring anchor the geophone cable, giving it a break strength that is either equal to or greater than the cable itself. The features of the SM-4 Geophone are shown in Figure-1[7].

Principles of operation: The SM-4 Geophone operates on the principle of moving coil. The relative movements between the magnet and coil generate a voltage between the ends of the coil. The coil is made of fine copper wire wound several times around the pole containing the permanent magnet with light springs connected at both ends of the pole. The Geophone is planted in firm contact with ground. Any vibration of the ground will affect the case and the suspended magnet. The coil wound around the pole will not move as quickly, so the magnet moves up and down past the coil.

The ends of the coil are connected to a "pigtail", a pair of wire which is equally connected to a damping resistor of 1000 Ω (1kΩ) and the wire extending from the case is connected through the cable to the recording equipment. The bits of current generated by the movements of the magnet make up the signal from the geophone. Geophones are designed to respond to extremely small ground displacements. A particle velocity of 0.1mm/s, which generates amplitude of 3 mV in a Geophone is caused by a displacement of the ground of only 160 nanometers at 100 Hz, the displacement is even smaller at higher frequencies[8]. The Geophone output is directly proportional to the strength of the magnetic field and the permanent magnet, number of turns in the coil, the radius of the coil, and the velocity of the coil relative to the magnet[9]. Modern high sensitivity geophones have an output of 0.5 to 0.7V for a velocity of 1cm/s of the ground. The Geophone coil and spring constitute an oscillatory system with natural frequency in the range from 7 to 30 Hz for reflection work and 4 to 10 Hz for refraction work[9].

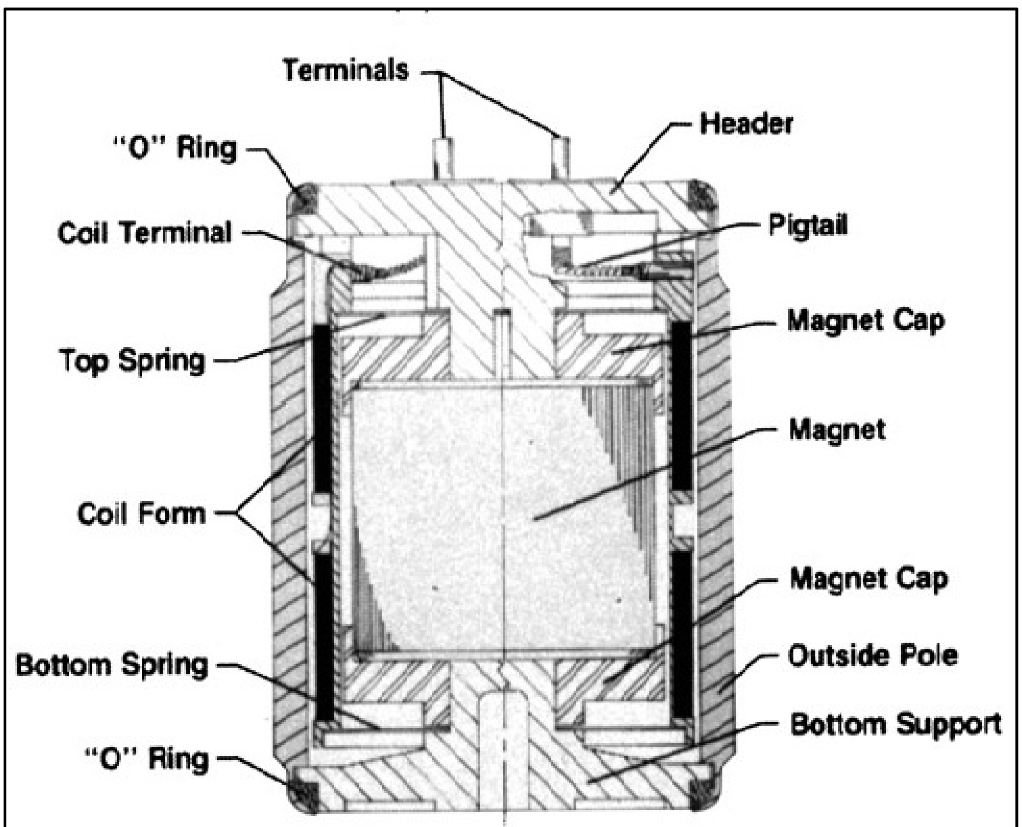

Figure-1: Schematic Features of a Typical Digital-Grade Geophone[7].

The Geophone spike is planted upright and contact is close enough into the ground to allow vibrations to be transmitted well from the earth to the Geophone. Good ground contact is necessary for better data acquisition, processing and interpretation.

Geophone sensitivity: The ability of a Geophone to convert ground motion into an output signal is directly related to its sensitivity. Sensitivity is a measure of the electrical output of the Geophone for a given mechanical input and is given in Volt/meter/second[10]. The sensitivity of Geophone is calculated from the formula for the Transduction Constant (G) and has a tolerance limit:

$$a = \frac{V}{v} = \frac{R_2}{R_1 + R_2} G \quad (1)$$

where: a = Sensitivity (V/m/s), Output Voltage (V), v = velocity (m/s) of geophone element, R_1 = Coil Resistance (Ω), R_2 = Load Resistance (Ω) and G = Electromechanical Coupling Coefficient (Transduction Constant).

Factors affecting the sensitivity of geophone: The sensitivity of any seismic detector is a function of various factors such as the inner and outer radii of coil, the axial thickness of the winding, the number of turns (N) of the coil and the strength of the magnet. These factors also affect the linear response time of the coil.

From equation (1) above, it can be observed that sensitivity is proportional to the number of turns of the coil and the strength of the magnetic field. The largest and the most likely influence on the sensitivity come from variation in the magnetic field strength of the magnet. This incidentally causes the change in damping. This means that as damping drops due to a weakening of the magnetic field, the sensitivity will also fall.

The coil resistance will generally stay within tolerance. The correlation of the sensitivity at a characteristic resistance of the coil at various bandwidths was conducted in this study. The coil resistance was measured directly using a Digital Multimeter of high percentage accuracy. The relationship between the sensitivity of the coil and the resistance is given as:

$$S = R_o\left(\frac{R_t}{N}\right) / [R_o + R_t] \quad (2)$$

When $\frac{R_t}{R_o}$ is less than unity, the sensitivity, S, approaches:

$$S = \frac{R_t}{N} \quad (3)$$

For the matching case where $R_t = R_o$, the sensitivity is about:

$$S = \left(\frac{R_o}{2N}\right) \quad (4)$$

Geophone with low sensitivity exhibits poor reception to weak signal. However, when the sensitivity is relatively high i.e. for a single Geophone, the changes and temperature characteristics of the magnetic flux intensity will result in large variability in Geophone's sensitivity.

Methodology

A signal generator was connected to a high resolution Cathode Ray Oscilloscope (CRO) input and a stable trace at a frequency of 10 Hz was obtained. The digital grade SM-4 Geophone was firmly planted in a sand box and connected to the second input of the CRO and then to the signal generator.

At maximum amplitude, various frequencies were applied to the Geophone and the various voltages (V) and Resistances (Ω) across the coil were recorded with the Digital Multimeter. An electrical integrity test was conducted on the Geophone to ensure that there is no current leakage. This was achieved by immersing the Geophone in a water tank and connecting it to a 12-Volt power source.

Signal generation: With the Geophone firmly planted in a sand box, mechanical vibrations of various frequencies were generated using a digital signal generator and an amplifier which boosts weak signals and compresses the range of signals. The permanent magnet in the Geophone was made to move up and down across the coil thereby generating vibrations which were detected and displayed by the CRO. The rate of up and down movement of the permanent magnet is a function of the applied frequency.

The higher the frequency, the faster will be the movement of the magnet. The voltage and the resistance across the coil were detected, displayed by the CRO and accurately measured by a Digital Multimeter.

Signal display: The output of the Geophone was too weak to be recorded without amplification. The useful range of amplitudes of the Geophone output extended from a few volts at the beginning of the recording to about 1μV near the end of the recording, several seconds after the drop. Signals weaker than 1μV are lost in the system as noise (a relative change or dynamic range of about 100dB)[9].

When current flows through the coil, the interaction between the field of the coil and the permanent magnetic field causes the coil to rotate, thereby deflecting the CRO beam transversely. The variable area trace is pictured as a result of the connection of the Digital Multimeter to the output of the Geophone to give the output voltage. This is repeated for various frequency bandwidths.

Results and discussion

Tables-1 to 5 shows the results of the motion of the Geophone displayed on the CRO.

Table-1: Characteristics of Geophone at Frequency Range of 0.5 – 10.0 Hz.

Frequency (Hz)	V_1 (Volts)	V_2 (Volts)	Average V (Volts)	Velocity (m/s)	Sensitivity (V/m/s)
0.5	2.62	2.66	2.64	0.10	26.40
1.0	2.97	3.01	2.99	0.14	21.36
1.5	5.26	5.30	5.28	0.17	31.06
2.0	7.46	7.50	7.48	0.20	37.40
2.5	7.88	7.94	7.91	0.22	35.96
3.0	8.10	8.16	8.13	0.25	32.52
3.5	7.55	7.63	7.59	0.27	28.11
4.0	6.95	7.03	6.99	0.28	24.96
4.5	6.55	6.61	6.58	0.30	21.93
5.0	6.20	6.28	6.24	0.32	19.50
5.5	5.97	6.04	6.01	0.33	18.21
6.0	5.84	5.88	5.86	0.35	16.74
6.5	5.60	5.62	5.61	0.36	15.58
7.0	5.50	5.56	5.53	0.37	14.95
7.5	5.39	5.47	5.43	0.39	13.92
8.0	5.30	5.38	5.34	0.40	13.35
8.5	5.25	5.27	5.26	0.41	12.83
9.0	5.18	5.24	5.21	0.42	12.41
9.5	5.15	5.19	5.17	0.44	11.75
10.0	5.14	5.14	5.14	0.45	11.42

Table-2: Characteristics of Geophone at Frequency Range of 5.0 – 100.0 Hz.

Frequency (Hz)	V_1 (Volts)	V_2 (Volts)	Average V (Volts)	Velocity (m/s)	Sensitivity (V/m/s)
5.0	2.34	2.40	2.37	0.32	7.41
10.0	2.34	2.41	2.38	0.45	5.29
15.0	2.59	2.68	2.64	0.55	4.80
20.0	2.71	2.81	2.76	0.63	4.38
25.0	2.46	2.54	2.50	0.71	3.52
30.0	2.29	2.38	2.34	0.78	3.00
35.0	2.18	2.27	2.23	0.84	2.66
40.0	2.10	2.18	2.14	0.89	2.41
45.0	2.04	2.12	2.08	0.95	2.19
50.0	1.99	2.07	2.03	1.00	2.03
55.0	1.95	2.02	1.99	1.05	1.90
60.0	1.92	1.99	1.96	1.10	1.78
65.0	1.89	1.96	1.93	1.14	1.69
70.0	1.87	1.94	1.91	1.18	1.62
75.0	1.86	1.92	1.89	1.23	1.54
80.0	1.84	1.91	1.88	1.27	1.48
85.0	1.83	1.89	1.86	1.30	1.43
90.0	1.82	1.88	1.85	1.34	1.38
95.0	1.81	1.88	1.85	1.38	1.34
100.0	1.81	1.88	1.85	1.41	1.31

Table-3: Characteristics of Geophones at Frequency Range of 50.0 – 1000.0 Hz.

Frequency (Hz)	V_1 (Volts)	V_2 (Volts)	Average V (Volts)	Velocity (m/s)	Sensitivity (V/m/s)
50	1.85	1.86	1.86	1.00	1.86
100	1.86	1.86	1.86	1.41	1.32
150	1.84	1.85	1.85	1.73	1.07
200	1.85	1.86	1.86	2.00	0.93
250	1.86	1.88	1.87	2.24	0.84
300	1.89	1.91	1.90	2.45	0.78
350	1.93	1.95	1.94	2.65	0.73
400	1.96	1.98	1.97	2.83	0.70
450	2.00	2.02	2.01	3.00	0.67
500	2.03	2.05	2.04	3.16	0.65
550	2.07	2.08	2.08	3.32	0.63
600	2.10	2.12	2.11	3.46	0.61
650	2.13	2.15	2.14	3.61	0.59
700	2.16	2.18	2.17	3.74	0.58
750	2.18	2.21	2.20	3.87	0.57
800	2.21	2.23	2.22	4.00	0.56
850	2.23	2.25	2.24	4.12	0.54
900	2.25	2.27	2.24	4.24	0.53
950	2.27	2.29	2.28	4.36	0.52
1000	2.29	2.31	2.30	4.47	0.52

Table-4: Characteristics of Geophones at Frequency Range of 500.0 – 10000.0 Hz.

Frequency (Hz)	V_1 (Volts)	V_2 (Volts)	Average V (Volts)	Velocity (m/s)	Sensitivity (V/m/s)
500	2.37	2.41	2.39	3.16	0.75
1000	2.38	2.40	2.39	4.47	0.54
1500	2.45	2.49	2.47	5.48	0.45
2000	2.49	2.53	2.51	6.32	0.40
2500	2.50	2.54	2.54	7.07	0.36
3000	2.51	2.53	2.52	7.75	0.33
3500	2.49	2.52	2.51	8.37	0.30
4000	2.47	2.51	2.49	9.04	0.28
4500	2.46	2.50	2.48	9.49	0.26
5000	2.45	2.49	2.47	10.00	0.25
5500	2.43	2.48	2.46	10.49	0.24
6000	2.42	2.47	2.45	10.96	0.22
6500	2.42	2.46	2.44	11.40	0.21
7000	2.41	2.46	2.44	11.83	0.21
7500	2.40	2.45	2.43	12.25	0.20
8000	2.40	2.45	2.43	12.65	0.19
8500	2.40	2.45	2.43	13.04	0.19
9000	2.40	2.45	2.43	13.42	0.18
9500	2.40	2.45	2.43	13.78	0.185
10000	2.40	2.45	2.43	14.14	0.17

Table-5: Characteristics of Geophones at Frequency Range of 5000.0 – 100000.0 Hz.

Frequency (Hz)	V_1 (Volts)	V_2 (Volts)	Average V (Volts)	Velocity (m/s)	Sensitivity (V/m/s)
5000	2.50	2.55	2.53	10.00	0.25
10000	2.51	2.56	2.54	14.14	0.18
15000	2.57	2.62	2.60	17.32	0.15
20000	2.64	2.71	2.68	20.00	0.13
25000	2.68	2.76	2.72	22.36	0.10
30000	2.65	2.74	2.70	24.50	0.11
35000	2.58	2.67	2.63	26.46	0.10
40000	2.43	2.54	2.49	28.28	0.09
45000	2.23	2.35	2.29	30.00	0.08
50000	1.88	2.09	2.04	31.62	0.07
55000	1.71	1.82	1.77	33.17	0.05
60000	1.42	1.52	1.47	34064	0.04
65000	1.13	1.23	1.18	36.06	0.03
70000	0.88	0.97	0.93	37.42	0.03
75000	0.65	0.72	0.69	38.73	0.02
80000	0.47	0.52	0.50	40.00	0.01
85000	0.35	0.38	0.37	41.23	0.01
90000	0.26	0.27	0.27	42.43	0.01
95000	0.20	0.21	0.21	43.59	0.01
100000	0.15	0.16	0.16	44.72	0.00

Figures-2 to 16 shows the response curves of the SM-4 Geophone at various frequency bandwidths. The characteristics of these response curves differ from voltage to velocity down to sensitivity.

Frequency-voltage response: Figure-2 shows that at a frequency range of 0.5 to 10.0 Hz, the voltage has a maximum value of 8.13 V when the natural frequency, f_o is 3 Hz. Similarly, for a bandwidth of 5.0 to 100.0 Hz in Figure-3, the maximum voltage is 2.7 V when the natural frequency, f_o is 20 Hz.

For the frequency bandwidth of 50 to 1000 Hz in Figure-4, the voltage is observed to be linear and later increased exponentially at a frequency of 50 Hz. Hence, the natural frequency of the geophone disappears. But at a frequency range of 500 to 10,000 Hz in Figure-5, the response curve for voltage changed and the natural frequency of the geophone reappears. It can be observed that at maximum amplitude of operation, the voltage of 2.54 V was recorded at a natural frequency, f_o of 2500 Hz.

It can also be observed that for a further frequency bandwidth of 5000 to 100,000 Hz in Figure-6, the natural frequency, f_o was analyzed to be 2500 Hz similar to that in Figure-5, though at a different voltage of 2.72 V against 2.54 V.

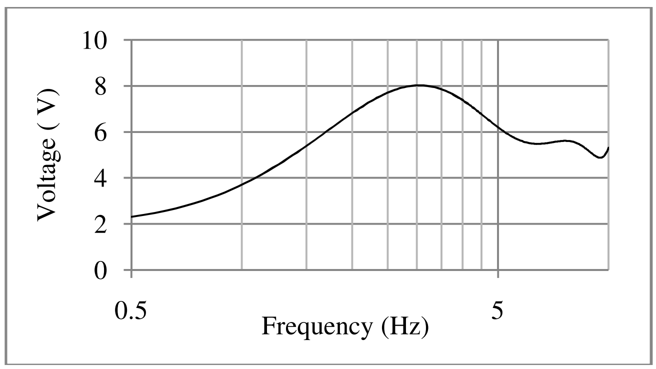

Figure-2: Frequency-Voltage Response (0.5-10 Hz).

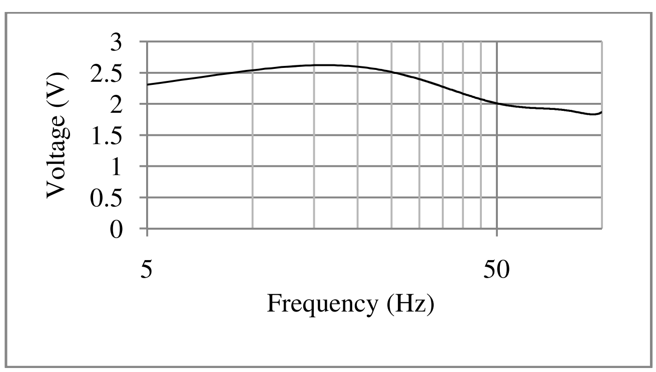

Figure-3: Frequency-Voltage Response (5-100 Hz).

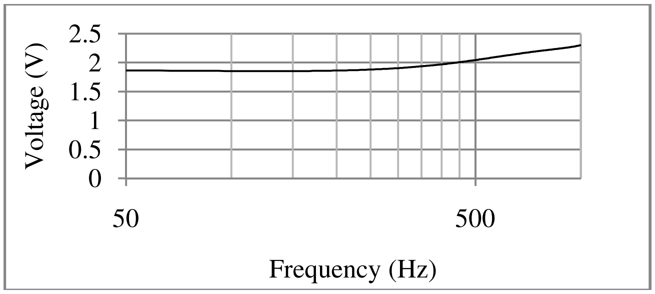

Figure-4: Frequency-Voltage Response (50-1000 Hz).

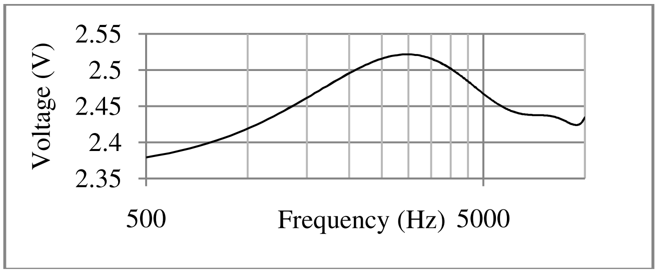

Figure-5: Frequency-Voltage Response (500-10000 Hz).

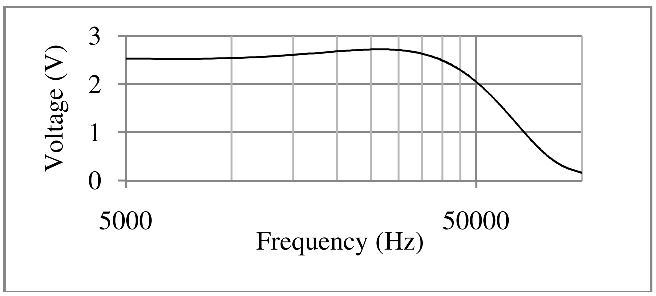

Figure-6: Frequency-Voltage Response (5000-100000 Hz).

Frequency-velocity response: The velocity of the permanent magnet across the coil of the geophone is observed to be proportional to the frequency during operation for all the frequency bandwidths. Figures-7, 8, 9, 10 and 11 respectively show the dependence of the velocity on the frequency of vibration of the Geophone. The velocity generally increases exponentially as the frequency increases implying that the higher the frequency of vibration, the greater the velocity of the Geophone during operations in the field. Hence, at maximum frequency of 100,000 Hz, the velocity is 44.72 m/s as compared with 0.10 m/s for the maximum frequency of 0.5 Hz.

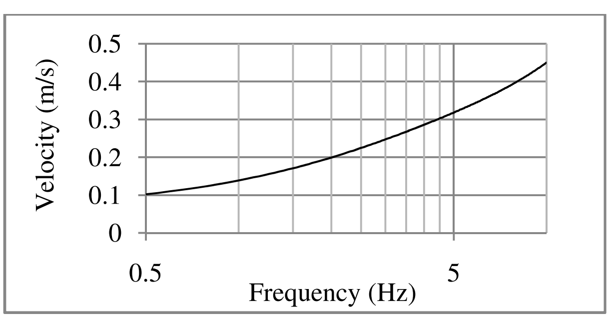

Figure-7: Frequency-Velocity Response (0.5-10 Hz).

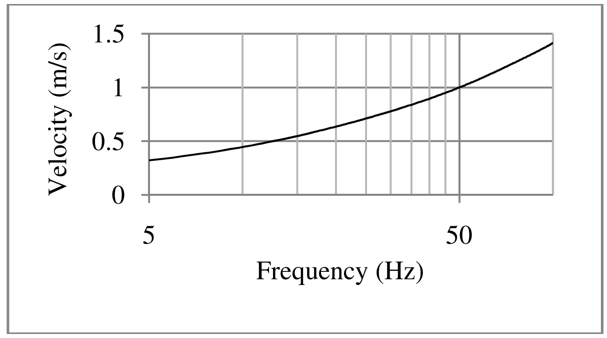

Figure-8: Frequency-Velocity Response (5-100 Hz).

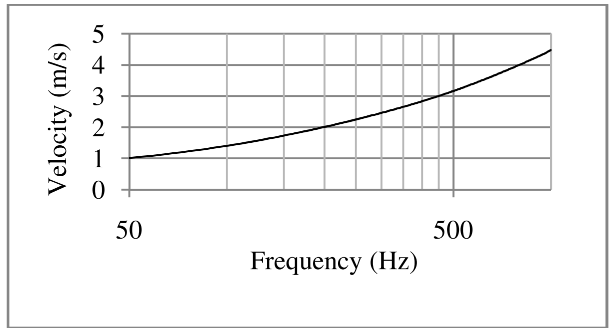

Figure-9: Frequency-Velocity Response (50-1000 Hz).

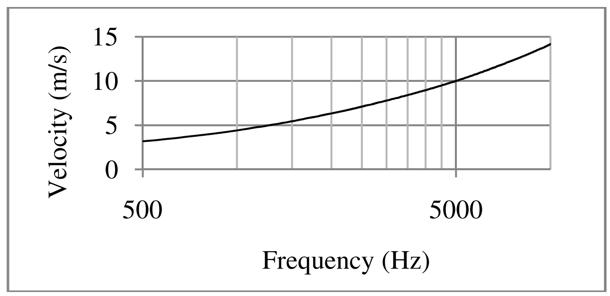

Figure-10: Frequency-Velocity Response (500-10000 Hz).

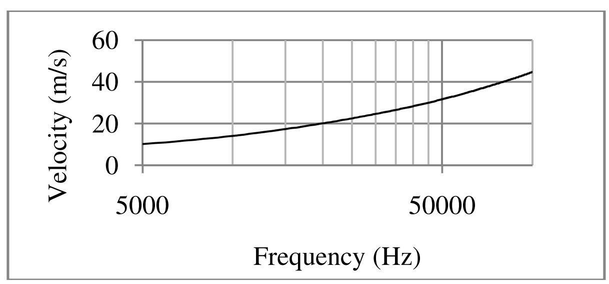

Figure-11: Frequency-Velocity Response (5000-100000 Hz).

Frequency-sensitivity response: Figure-12 reveals that at a maximum sensitivity of 37.40 V/m/s, the natural frequency of the geophone is observed to be 2 Hz and coil resistance of 282 Ω for frequency range of 0.5 to 10.0 Hz. An exponential decrease in sensitivity of the Geophone is also observed. The factor responsible for this is the rapid decrease of the characteristic coil resistance from 282 to 108 Ω. Increase in the frequency range from 0.5 to 10.0 Hz to 5.0 to 100.0 Hz may also be responsible. For the frequency bandwidth of 5 to 100

Hz, the sensitivity is observed to decrease exponentially with increasing frequency from 7.41 to 1.31 V/m/s (Figure-13). At a further frequency bandwidth of 50 – 1000 Hz, the natural frequency of the Geophone disappears (Figure-14). The sensitivity is observed to be on exponential decrease with increasing frequency from 0.75 to 0.71 V/m/s which is at a constant change with the frequency of the magnet across the coil. In Figure-15, the sensitivity is still on exponential decrease even at an increase in frequency for a bandwidth of 500 to 10000 Hz. Figure-16 reveals that for a frequency bandwidth of 5000 to 100000 Hz, sensitivity decreases exponentially from 0.25 to 0.00 V/m/s. This is as a result of distortion in the Geophone element (spring). The characteristic coil resistance decreased to 100 Ω and this caused the Geophone sensitivity to approach zero. This is consistent with standard values.

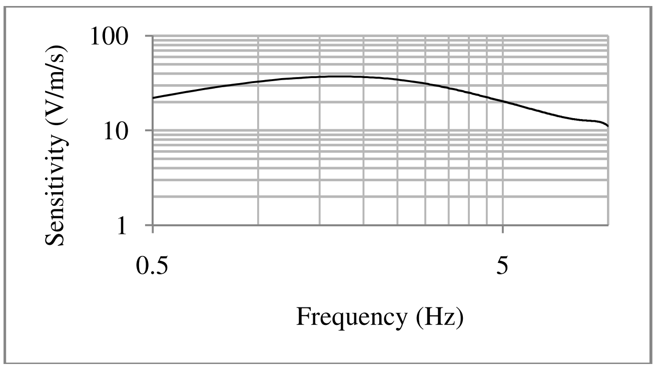

Figure-12: Frequency-Sensitivity Response (0.5-10 Hz).

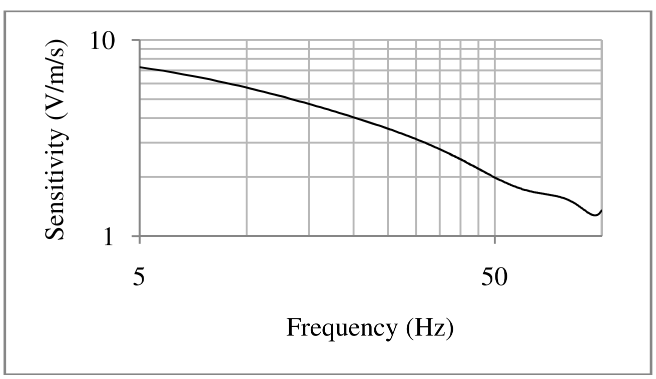

Figure-13: Frequency-Sensitivity Response (5-100 Hz).

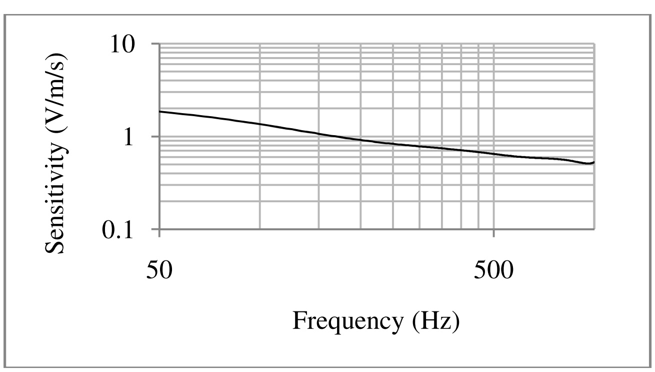

Figure-14: Frequency-Sensitivity Response (50-1000 Hz).

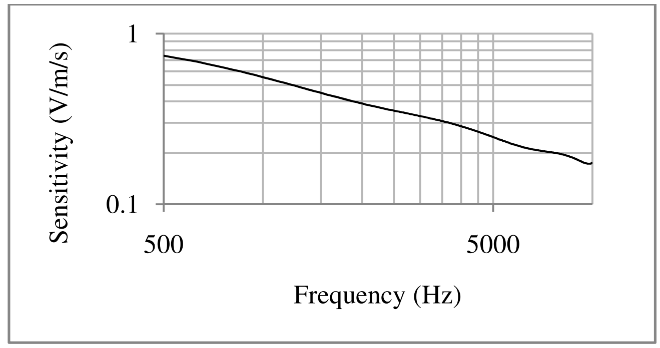

Figure-15: Frequency-Sensitivity Response (500-10000 Hz).

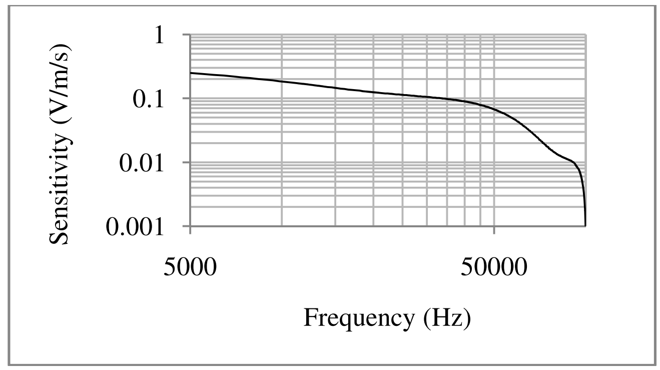

Figure-16: Frequency-Sensitivity Response (5000-100000 Hz).

Discussion: The dependence of voltage and sensitivity on the characteristic coil resistance and the frequency during operation is clearly shown in Figures-2, 3, 4, 5 and 6 and 12, 13, 14, 15 and 16 respectively. Hence, the correlation between the voltage, V and the sensitivity, V/m/s with the difference in frequency is considered on a very wide range of frequency.

However, the performance of the Geophone coil is observed to be a function of the characteristic coil resistance. When the characteristic coil resistance was changed from 282 Ω to 375 Ω with the bandwidth unchanged, the Geophone was observed to have a natural frequency of 12 Hz, i.e. at a frequency bandwidth of 0.5 – 10.0 Hz, against the manufacturer's 10 Hz. At a lower coil resistance value of 368 Ω, the natural frequency drops to 10 Hz. This implies that a Geophone with a very high coil resistance will definitely have a high natural frequency. These results agree with theoretical predictions and manufacturer's specification of the SM-4 digital grade Geophone where sensitivity is specified as 28.8 V/m/s for a coil resistance of 375 Ω and natural frequency of 10 Hz[5].

Conclusion

This experimental investigation into the sensitivity of SM-4 Geophone that has been in use in Nigeria for seismic data acquisition and its performance indicates that experimental results and standard measurements show that the sensitivity of the SM-4 Geophone is dependent on the frequency, the permanent magnet and the terminal resistance of the coil. In addition, higher sensitivity greater than 1V/m/s and optimal value of voltage can be obtained if the frequency does not exceed 100 Hz and if the difference between the inner and outer radii of the coil is not more than 4 cm.

The performance of the permanent magnet across the coil is also dependent on the frequency under which the Geophone operates. Specifically, the performance of the magnet tends to increase with increasing frequency. However, the sensitivity of the SM-4 Geophone tested decreases with increasing frequency. This negative effect is attributable to distortion of the Geophone element and several years of usage.

Recommendation: With the observed drop in sensitivity and its negative impact on the performance of the SM-4 Geophone used in this study, it is recommended that these Geophones be replaced with improved ones after some years of constant use, and after the expiration of the manufacturer's warranty period of three years. Furthermore, regular testing of the various parameters on which the performance of the Geophone hinges should be conducted using more sophisticated equipment. This is to ensure good data quality and avoid failure of the Geophone element and attendant increase in running cost of the seismic crew. Besides, in view of the need to map deeper subsurface structures, recent and sophisticated Geophones with ultra-high sensitivity should be employed by seismic exploration companies in Nigeria.

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